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PRESSURE VESSEL REINFORCEMENT PAD DESIGN BY FINITE ELEMENT ANALYSIS

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ABSTRACT

This research aims to study and compare several reinforcement pad design or repad on a pressure vessels based on finite element analysis. Present study is focused on pressure vessel component such as nozzle, repad and shell to nozzle intersection area. Results from finite element analysis performed on repad from previous works were discussed. The repad design as outlined in American Society of Mechanical Engineers Boiler and Pressure Vessels Code were adopted by most researchers as reported in the literatures. Common repad configurations and findings from analysis were discussed. Results from previous studies on the effect of stress concentration factor, d/D ratio, effect of elastic stress and buckling effect on structure nozzle to shell junction were summarized in this paper.

***KEYWORDS:** Pressure Vessel, Finite Element Analysis, Repad, Reinforcement Plate & Intersection*

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Original Article

1. INTRODUCTION

Pressure vessel is common equipment extensively used in various industries from petrochemical, oil and gas processing industries, power plants and mining. The pressure vessels function either as liquid container or chemical storage contains pressure for normal, critical and severe product processing. The design of pressure vessel was originated by Leonardo da Vinci in 1490s as documented in old manuscript design book known as Codex Madrid I. Earlier concept of pressure vessel as pressurized air containers that lifts the heavy weight underwater (Abdolreza, 2019). From time to time, the pressure vessel and its components are wisely designed in order to reduce risk of disastrous failure that may result life accident. There are quite number of incidents happened due to pressure vessel failures since the beginning of industry revolution era in 1911s. Public health safety had been given attention thus American Society of Mechanical Engineers (ASME) took the initiative to established proper guideline to design and manufacture safe pressure vessel. The initially publication of pressure vessel construction code was developed in 1914s which known as ASME Boiler and Pressure Vessel Code (BPVC). The design of pressure vessel and its components has been significantly improved since then. In pressure vessel, nozzle is one of critical part commonly used as apparatus connecting pressure vessel with the complete operation system. Many research works concluded common failure pressure vessels observed at nozzle to junction vicinity. Nozzle carries load from external piping system and also sustain load from internal pressure. This paper presents concept of reinforcement design and findings results from design assessment by finite element analysis of repad on pressure vessel.

2. THEORIES OF BEHAVIOUR STRESS AND BUCKLING ON PRESSURE VESSEL

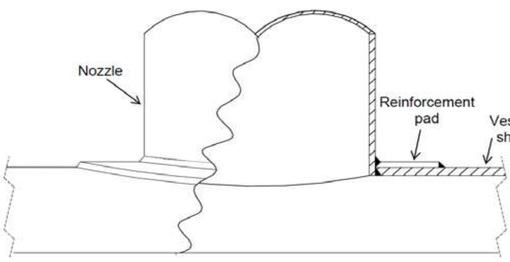
Early work by Gill in 1970 had performed study on stress analysis of pressure vessels and pressure vessel components (Gill, 1970). The study conducted experimentally on metallic pressure vessels components. Works performed to analyze nozzle reaction in pressure vessel with detail elastic analysis on shell and stress concentration factor for nozzle in vessel under pressure, shear and moment loadings. Gill concluded reaction stress on the nozzles affected by stress intensity at nozzle junction area.

Further studies by Kitching *et. al* on the effect of stress concentration factor (SCF) when repad installed in vicinity nozzle to shell junction area (Kitching, 1976). They concluded that the SCF reduced significantly when repad was installed around nozzle to shell junction area. The study determined the used of repad found to be more safer and economic design compared with the used of self-reinforced nozzle or integral type nozzle. The study was in agreement with previous research by Rodabough (Wichman, 1965).

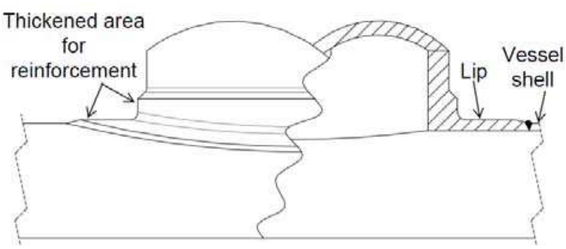
Szyzkowski and Glockner studies different nozzle configuration on pressure vessel. They proposed buckle free design pressure vessel head with nozzle install on the head subjected to internal pressure (Szyzkowski, 1987). They concluded an effective method to reduce circumference membrane stress that possibly caused a buckling failure at head was by controlling depth of head dimension. Shi *et. al.* studied an effect of buckling analysis of cylindrical shell and stress at nozzle junction area (Shi, 2017). They concluded that the effect to local buckling at nozzle junction can be reduced by using repad at the nozzle junction area.

3. DESIGN OF REINFORCEMENT PAD

Several methods to design repad of reinforcement pad have been made available (McIntyre, 1977). There was no difference made between the repad of vessel by locally increased shell thickness or by addition of repad welded on either inside or outside surface on the pressure vessel shell. Repad typically installed at outside of shell opening in vicinity branches or junction nozzle to shell. Repad design subjected to internal pressure and limitation of uses was outlined in ASME BPVC (ASME, 2017). Common type repad used in accordance ASME BPVC requirement as shown in figure 1.



(a)



(b)

Figure 1: Common Type of Repad at Pressure Vessel, (a) Nozzle with Repad and (b) Nozzle with Self-Reinforced Type (Mohammed, 2016).

Total cross section area of required reinforcement A, in any given plane through the opening for shell or head under internal pressure can be obtain from (1), where A denotes area reinforced required, d_r denotes diameter nozzle required, F denoted correction factor, t_n denotes nozzle wall thickness, t_r denotes required shell thickness and f_r denotes strength reduction factor.

$$A = d_r F + 2t_n t_r F(1 - f_{r1}) \tag{1}$$

ASME BVPC has established guideline to design repad for pressure vessel opening. Repad should be formed as closely to the curvature of the vessel shell surface as possible. While normally repad put on the outside of the vessel body, repad can also be put inside providing they do not interfere with vessel operation. There are three methods for calculating the strength of reinforcement required for opening in pressure vessel. The methods are area replacement rules, FEA and membrane-bending stress analysis that can be determine from (2), where S_m denotes membrane stress, P denotes internal pressure, R denotes radius, R_n denotes radius nozzle, R_m denotes radius mean shell, t_n denotes thickness nozzle, t_e denotes thickness between neutral axis and A_s is required area (ASME, 2017).

$$s_m = P\left(\frac{R\left(R_n + t_n + \sqrt{R_m t}\right) + R_n\left(t + t_e + \sqrt{R_{nm} t_n}\right)}{A_s}\right) \tag{2}$$

4. FEA AND STUDIES ON REINFORCEMENT PAD BY PREVIOUS WORKS

Previous works by McBride *et. al.* had performed experiment pressure test on actual model of steel pressure vessel with reinforcement pad of 14.3 mm thick carbon steel material installed outside the vessel surface. They found the used of repad could reduce the nozzle stress intensity when the pressure vessel subjected to internal pressure (McBride, 1980). Other works used 6 mm of carbon steel plate as reinforcement pad for its vessel model for the experiment of influence of repad on limit and burst at nozzle junction. They concluded the used of repad had increase limit and burst when the pressure vessel subjected to internal pressure (Xue, 2003). Other studies performed an experiment in pressure vessel with 12.7 mm thick of carbon steel repad installed on the vessel to determine stress concentration factor (SCF) at the repad. The study established F factor to determine suitable SCF compared with previous method where SCF uniformly 1.0 was used designed the repad for all nozzle sized (Taagepera, 2006).

As computer programming and with the development technology in simulation and analysis, more adaptive method and tools has been made available for designer to design pressure vessels and its components. FEA was widely used by designer and researcher to perform local analysis on pressure vessel parts particularly on repad design. There are many works adopted FEA as tools for design and analysis of repad. Researcher benefit by the use of FEA in order to verify the design with the available specification such as ASME BVPC guideline, welding research council bulletin (WRC) and established theories and numerically.

4.1 FEA Repad Based on ASME Guideline

Mohamed *et. al.* has performed FEA to study the comparison between separate repad type and integral reinforced pad type on nozzle pressure vessel under cyclic loading. The FEA had been performed at repad and nozzle part based on area replacement rule as per ASME UG-36 (b). They found that the uses of separate repad configuration not able to withstand the imposed cyclic loads when accumulated fatigue damage occurred compared with nozzle with integral reinforced type. They recommended self-reinforced or self-integral type nozzle to be used when nozzles for vessel operated under cyclic loadings conditions subjected to internal pressure (Mohamed, 2016).

Bhupendra *et. al.* has deployed FEA to analyze stress on nozzle by varying nozzle opening angle and nozzle location with repad and without repad configuration. Complete unit vessel was selected as design model with shell plate thickness on 25.4 mm, repad thickness of 50 mm attached outside surface in the vicinity of nozzle intersection area. The

vessel was analyzed based on normal operation loading and internal pressure of 30.26 barg. From the analysis, they concluded that stress at nozzle found to be lower when nozzle with repad are installed compared to nozzle without repad. The stress value on nozzle also depends on nozzle offset and inclination angle. Higher stress value recorded when inclination angle was increased observed for nozzle without pad (Bhupendra, 2018).

Eyas *et. al.* studied failure criteria on steel tanks parts includes nozzle with repad installed on outside shell surface. FEA has been carried out to determine potential mutilation and prediction number of fatigue cycle prior to failure (Eyas, 2019). They concluded that higher in alternating stress S_{alt} resulted to lower number of design life cycle as shown in figure 2. The alternating stress can be obtained from (3) where K_f denotes fatigue reduction factor, K_e denotes fatigue penalty factory and S_p is secondary loading factor.

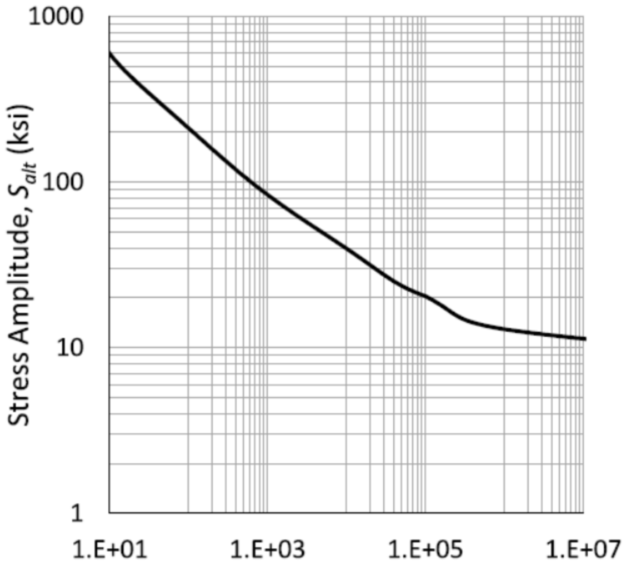


Figure 2: Discontinuous Equivalent Stress and Design Cycles Numbers Corresponding to Stress Amplitude (Eyas, 2019).

$$S_{alt} = \frac{K_f K_e \Delta S_p}{2} \tag{3}$$

4.2 FEA Repad Based on WRC

Several edition of bulletin has been published by Welding Research Council (WRC) United Engineering Center in New York. The WRC bulletin provides comprehensive experimental investigations into elastic-plastic behavior of pressure vessel components including repad. The most adopted bulletin are WRC 297 and WRC 329 both commonly used by researcher as comparison with result obtained from FEA carried out on pressure vessel components. WRC bulletin had classified type of stresses available when pressure vessel carried nozzle loadings from piping and subjected to internal pressure. The type is membrane stress, radial bending and circumferential bending where ASME BPVC Division 2 had adopted the basis and included in their standard as shown in figure 3.

Preuter had adopted ANSYS software to carry out FEA on nozzle to shell intersection with repad and without repad for the pressure vessel subjected to internal pressure and with primary loadings as per figure 3. Preuter concluded that nozzle with repad sustained more loads imposed by cyclic loadings and capable in attenuated the stress (Preuter, 2015). Work by Pathre had adopted commercial software CEASER II studied pipe stress on nozzle intersection by

evaluating stress as per WRC 297 guideline found that the result was in agreement with Preuter. Charles *et. al.* selected WRC 329 to study the effect of SIF for nozzle on branch connection.

Stress Category	Primary			Secondary Membrane plus Bending	Peak
	General Membrane	Local Membrane	Bending		
Description (For examples, see Table 5.2)	Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Average stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads.	Component of primary stress proportional to distance from centroid of solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations.	1. Increment added to primary or secondary stress by a concentration (notch). 2. Certain thermal stresses which may cause fatigue but not distortion of vessel shape.
Symbol	P_m	P_L	P_b	Q	F

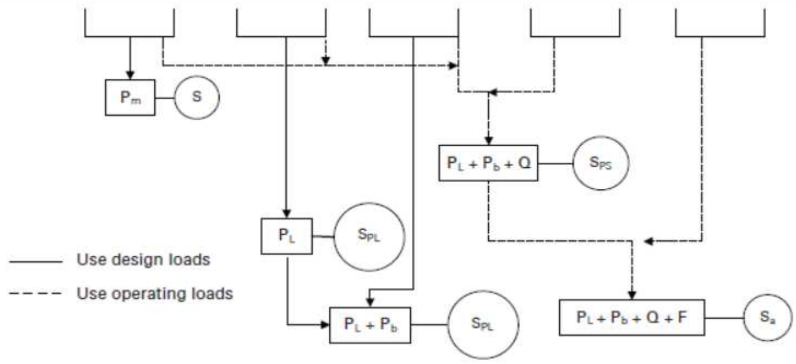


Figure 3: Stress Categories and Elastic Stress Limits (ASME BPVC, 2017).

Charles had identified inaccuracies of SIF in WRC 329 bulletin and proposed equation to determine accurate SIF as shown in (4), where *T* denotes nominal wall thickness, *t* denotes nominal thickness of branch and *D* denotes mean diameter shell (Charles, 2016).

$$0.75\frac{t}{T} - 0.89\left(\frac{t}{T}\right) + 0.18\left(\frac{D}{T}\right)^{0.34} \tag{4}$$

4.3 FEA Repad Based on Theories and Numerical Method

In early 1993, effort was made to develop special purpose computer software namely Stress Analysis in Intersecting Shells (SAIS) from parametric study on shell and nozzle intersection area based on Hellinger-Reissner mixed principal (Skopinsky, 1993). The SAIS computer program had been further improved in 1999 by modifying algorithm from the basis SAIS program. The finite element method (FEM) based on modified mix formulation and two dimensional shell theories has been used to analyze the shell intersections. The SAIS program has capability to calculate maximum effective stresses in pressure vessel ellipsoidal head, nozzle and repad and its position (Skopinsky, 2002).

Many researchers adopted FEA as tool to perform analysis particularly on nozzle to shell junction or intersections subjected internal pressure. The FEA works performed, then verified by numerical method or appropriate equations (Chen, 1993, Skopinsky, 1999, Xue 2010, Tipple, 2012, Gupta, 2014, Shantkumar, 2015, Ramesh, 2016, Jargal, 2016, Nikam, 2016, Mukhtar, 2017 and Liu 2017). Previous works focus on effect SIF, d/D ratio, structural behaviors due to elastic stress

and buckling effect subjected to internal pressure and nozzle loadings. It was observed that all studies conducted based on basic configuration repad attached at nozzle to shell intersection outside pressure vessel body.

5. CONCLUSIONS

- Recent trend studies on pressure vessel component particularly on the advantage of repad in vicinity opening nozzle on pressure vessel as part to strengthen the nozzle is still relevant. The use of FEA as a tool to analyse the component is sought and capable to improve the design.
- All study focus on typical geometry repad installed outside the vessel body. Present study proposes to focus the study with alternative geometry repad installed inside the vessel body while the internal pressure is still primary source of loads on a pressure vessel.

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